

Performance of the PRIMEX Electromagnetic Calorimeter

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Abstract. We report the design and performance of the hybrid electromagnetic calorimeter for the PRIMEX experiment at Jefferson Laboratory. The detector was designed, constructed and used for high precision measurement of the lifetime of the neutral pion via the Primakoff effect. Calorimeter installation and commissioning was completed with first physics run in fall of 2004. Especially we present calorimeter energy and position resolution at the transition region between PWO crystals and lead glass.

Keywords: calorimeter, photon, energy resolution

INTRODUCTION

Measurement of the partial width of the decay $\pi^0 \rightarrow \gamma\gamma$ provides an unique test of low energy QCD in confinement scale regime. The experiment PRIMEX (Primakoff Experiment) ?? was designed to make a high precision (one percent level) measurement of this decay. Tagged photon beam at Hall B of the Jefferson Laboratory was used for forward production of neutral pions in the Coulomb field of the target nucleus (Primakoff effect). The two photons from the pion decay are detected in the Hybrid Calorimeter (HYCAL). The HYCAL was designed to provide high efficiency registration of the photons with high resolution in energy and space. In present talk we describe physics requirements for calorimeter, design and construction of the setup, calibration and performance during the physics data taking. We summarize calorimeter characteristics in the conclusion.

PHYSIC REQUIREMENTS

As we measure absolute value of the cross section high photon efficiency is essential for precise measurements as well as accurate monitoring of the tagged photon beam. The Primakoff production cross section is peaked at 0.3mrad for nucleon target at energies of this experiment ($E_\gamma = 4.9 - 5.5\text{GeV}$).

High angular and energy resolutions are required to cleanly distinguish the Primakoff mechanism from π^0 production by other processes, and good invariant mass reconstruction is essential for rejection of backgrounds.

Using Intensive Monte Carlo studies and data from the beam test of the prototypes we formulated requirements for the calorimeter performance:

$\gamma\gamma$ invariant mass resolution is to be better than $2.5 \text{ MeV}/c^2$

angular resolution for reconstructed π^0 is better than 0.35 mrad.

DESIGN OF THE CALORIMETER

We have chosen a hybrid calorimeter scheme where the central part of the detector is made of high resolution scintillating crystals with a hole in the middle for the passage of the photon beam and the peripheral part is consisting of lead glass Cherenkov modules. To ensure high performance of the calorimeter the central part of the detector was constructed from 1152 lead tungstate (PWO) scintillating crystals surrounded with 576 lead glass blocks. The transverse dimensions of the HYCAL ($116 \times 116 \text{ cm}^2$) were chosen to have sufficient geometrical acceptance with fixed central hole ($4 \times 4 \text{ cm}^2$) in the middle of the detector. This design is based on an optimization of the cost and performance of the calorimeter. It allows us to have maximal efficiency for π^0 decay photons without prohibitive cost of the large area crystal calorimeter. At a distance of 7.3 m from the production target, the calorimeter has about 70% geometrical acceptance for forward neutral pions. Since the area around the photon beam is under high rate irradiation the crystals used should be radiation hard. The best crystals available now are lead tungstate (PbWO_4) which were developed for the CMS Electromagnetic Calorimeter Collaboration at Russia and China. Since the Russian crystal production is saturated by LHC experiments under construction we worked with Shanghai Institute of Ceramics which provided the crystals of high quality under our strict specifications. The crystals dimensions of $20.5 \times 20.5 \times 180 \text{ mm}^3$ were chosen. The individual crystals were wrapped in $100 \mu\text{m}$ VM2000 sheets. The crystals were viewed by the Hamamatsu R4125HA photomultiplier tubes coupled to them with optical grease. As the PWO crystal light yield is highly temperature dependent (2%/degC at room temperature) and increasing with decrease of temperature, so temperature stabilization of the calorimeter is mandatory. The operational temperature was chosen to be 14°C using cooled water circulation through tubes installed in the outer body of the calorimeter to provide thermal stabilization.

The lead glass modules supplied by IHEP (Serpukhov, Russia) with dimensions $38 \times 38 \times 450 \text{ mm}^3$ were made from the same type of glass used in many experiments at high energies and in the Jefferson Laboratory and its properties are well known. The lead glass blocks are wrapped in $25 \mu\text{m}$ aluminized Mylar foil. The Cherenkov light produced in lead glass radiator is detected by The FEU-84-3 photomultiplier tube.

The photograph of the detector during assembly is shown in Fig. ?? The HYCAL calorimeter on its support stand in the run configuration is shown in Fig. ??

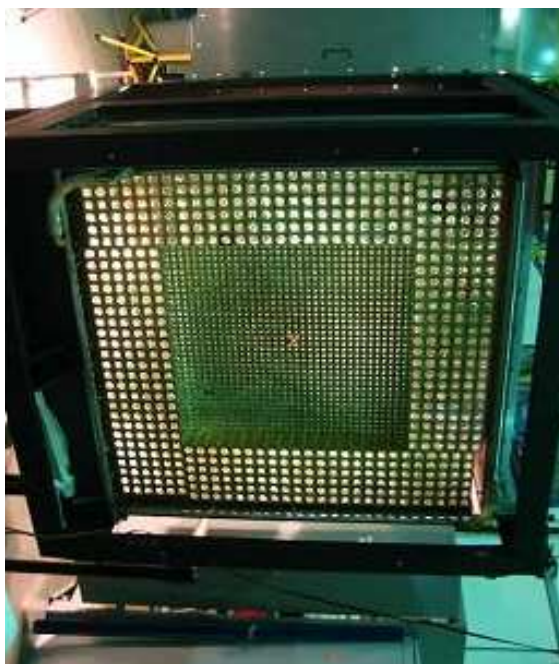
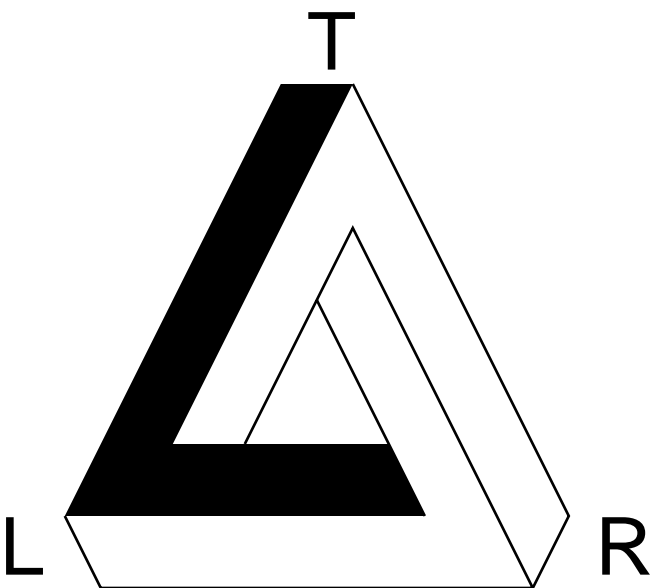


FIGURE 1. Photograph of the HYCAL calorimeter during assembly: crystal and lead glass arrays are shown

FIGURE 2. Scheme of the HYCAL calorimeter



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Abstract. We report the design and performance of the hybrid electromagnetic calorimeter consisting of 1152 $PbWO_4$ crystals and 576 lead glass blocks for the PrimEx experiment at the Jefferson Laboratory. The detector was built for high precision measurement of the neutral pion lifetime via the Primakoff effect. Calorimeter installation and commissioning was completed with the first physics run in fall of 2004. We present the energy and position resolution of the calorimeter. Obtained π^0 mass resolution of $1.3\text{MeV}/c^2$ and its production angle resolution of 0.34mrad demonstrate the ability of the experiment to extract the π^0 lifetime on one percent level.

Keywords: calorimeter, photon, energy resolution

INTRODUCTION

Measurement of the partial width of the decay $\pi^0 \rightarrow \gamma\gamma$ provides an unique test of low energy QCD in confinement scale regime. The π^0 lifetime is arguably the most precise theoretical calculation in low energy QCD, which in the leading order depends on fundamental parameters only. The contribution of the next-to-leading order does not exceed 4% of the leading-order prediction [1]. The experiment PrimEx [2], [4] was designed to make a high precision (at one percent level) measurement of the π^0 decay width. The tagged photon beam at Hall B of the Jefferson Laboratory [3] was used for forward production of neutral pions in the Coulomb field of the target nucleus (Primakoff effect). The two photons from the pion decay are detected in the Hybrid Calorimeter (HYCAL). The HYCAL was designed to provide high efficiency detection of the photons with high resolution in energy and space. Here we describe the physics requirements for the calorimeter, the design and construction of the setup, and its calibration and performance during the physics data taking. We summarize calorimeter characteristics in the conclusion.

PHYSIC REQUIREMENTS

Precision measurement of an absolute value of the Primakoff π^0 production cross section requires a photon detector with high energy and space resolutions. Yet another condition is accurate monitoring of the energy and intensity of the tagged photon beam. The Primakoff production cross section is peaked at $\sim 0.3\text{mrad}$ for a nucleon target at energies of this experiment ($E_\gamma = 4.9\text{--}5.5\text{GeV}$). Therefore, high angular resolution is required for clear separation of this mechanism from the other processes at forward angles. Likewise, accurate reconstruction of the two-photon invariant mass is essential for rejection of background. Based on these requirements, we formulated the design concepts for the calorimeter on the Monte-Carlo level and then built prototype detectors that were tested in the beam [7]. Finally, we were able to construct the PrimEx detector whose design and performance are described below.

DESIGN OF THE CALORIMETER

To optimize the performance and cost of the detector, we have chosen a hybrid calorimeter design combining novel $PbWO_4$ scintillating crystals and conventional Cherenkov lead glass detectors. The central part of the calorimeter is built of 1152 $PbWO_4$ crystals surrounded with 576 lead glass blocks. The transverse dimensions of the calorimeter ($116 \times 116 \text{cm}^2$) are sufficient for a large geometrical acceptance for the π^0 mesons emitted at zero angle from the production target located 7.3 m upstream of the detector ($\sim 70\%$). Since the area around the photon beam is under a high rate of irradiation, the crystals used should be radiation hard. The $PbWO_4$ crystals fully meet the latter requirement.

In the past 10-15 years, the $PbWO_4$ crystal development resulted in improved light output that provides a good energy resolution. Furthermore, due to very strict requirements by LHC calorimetry groups [5], high quality and radiation hard $PbWO_4$ crystals became commercially available from the two basic manufacturers: BTCP, Russia [6] and Shanghai Institute of Ceramics (SIC), China. For the HYCAL calorimeter we have received 1250 crystals from SIC, China. The dimensions of the individual crystals are $20.5 \times 20.5 \times 180 \text{mm}^3$. To improve light collection, the crystals were wrapped in $100\mu\text{m}$ VM2000 reflective material [7] and then, for light isolation between the neighbours, in $36\mu\text{m}$ Tedlar. The crystals were viewed by Hamamatsu R4125HA photomultiplier tubes coupled to them with optical grease. As the $PbWO_4$ crystal light yield is highly temperature dependent ($\sim 2\%/^\circ\text{C}$ at room temperature), temperature stabilization of the calorimeter is mandatory. Throughout the experiment, the calorimeter was operated at $14 \pm 0.1^\circ\text{C}$ temperature, which was maintained by circulation of the cool liquid around the outer body of the calorimeter assembly.

The lead-glass modules of the calorimeter were provided by the IHEP (Russia) group [8]. The individual modules with the size of $38.2 \times 38.2 \times 450 \text{mm}^3$ (SF-2 type) were wrapped by $25\mu\text{m}$ aluminized mylar foil. The Cherenkov light produced in the lead glass radiator was detected by the Russian-made FEU-84-3 photomultiplier tubes.

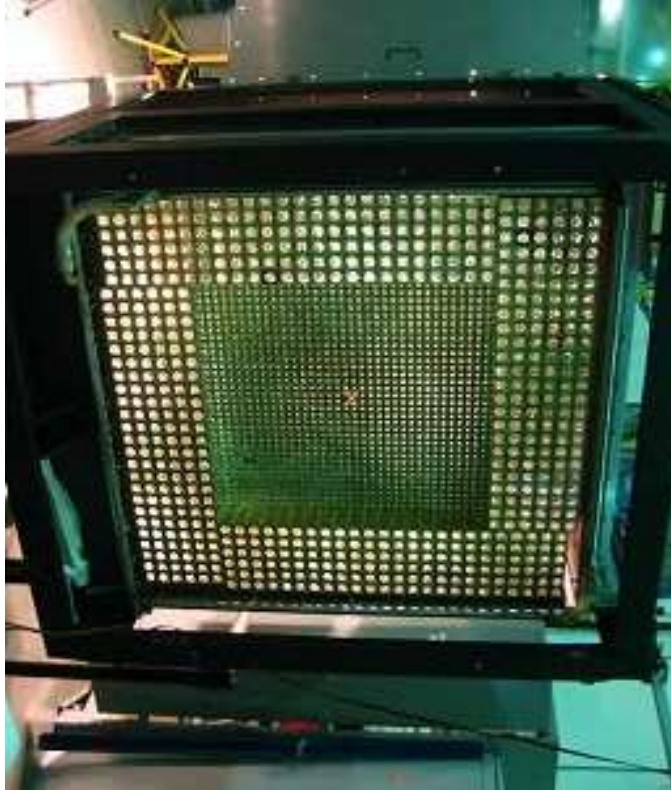


FIGURE 1. Photograph of the HYCAL calorimeter during assembly: crystal and lead glass arrays are shown

The photograph of the detector during the assembly at the TestLab of the Jefferson laboratory is shown in Fig. 1.

The PrimEx experiment utilized the CODA DAQ system. The digital information was read out from over 2200 channels of FASTBUS based ADC and TDC. An advantage of this system is the ability to operate in fully buffered mode. Namely, events are buffered in the digitization modules themselves allowing the modules to be "live" during the readout process. This significantly reduced the dead time of the DAQ, which is essential for the cross-section measurement.

CALIBRATION

In order to maintain high performance of the calorimeter, a periodic energy calibration with tagged photon beam was required. During the experiment, HYCAL was calibrated by illuminating each module with a low-intensity tagged-photon beam. The entire assembly with weight of about five tons was movable in the transporter frame in both horizontal and vertical directions with a position accuracy of $\pm 0.7mm$. The calorimeter position was remotely controlled during the calibration.

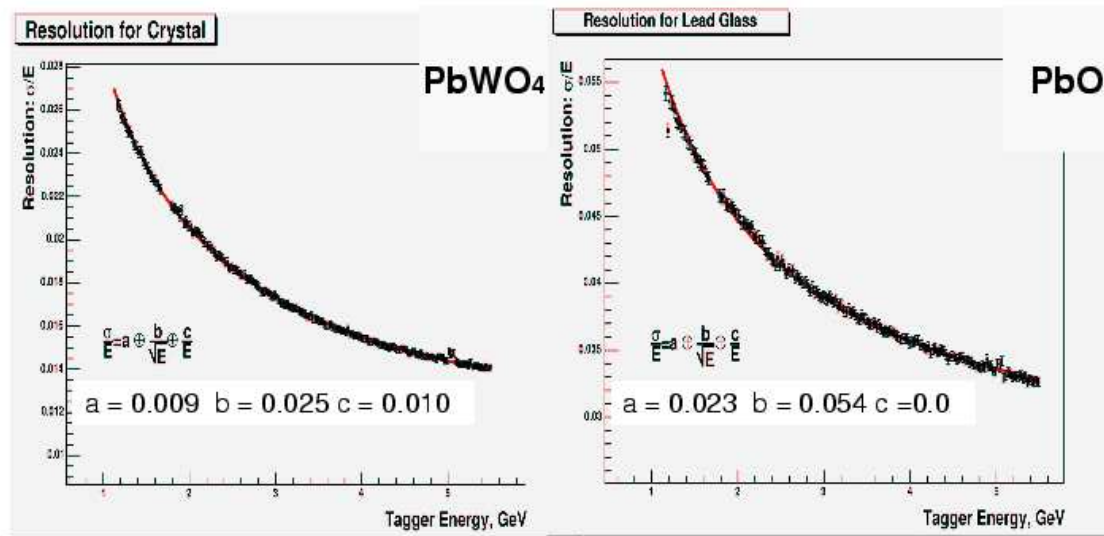


FIGURE 2. Energy resolution of the $PbWO_4$ crystals and the lead glass as function of the primary photon energy.

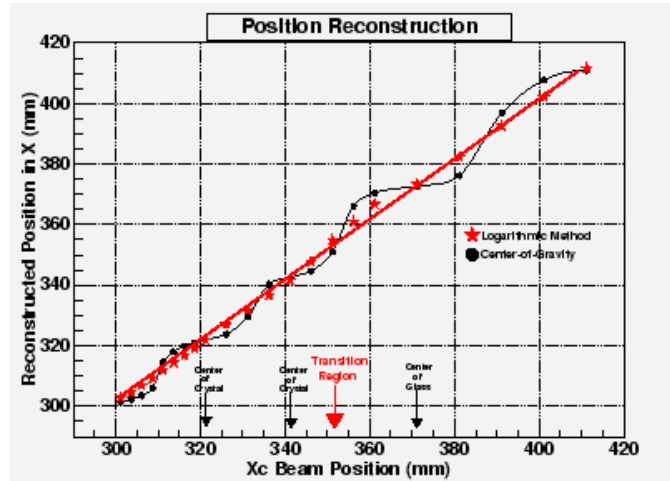


FIGURE 3. Shower position reconstruction in the calorimeter.

The tagged photon beam irradiated each module of the calorimeter using "a snake scan" during the calibration runs. Relative gains of the modules and energy dependence of the detector resolution, as determined through calibration, are shown in Fig. 2 for the $PbWO_4$ and lead-glass parts of the detector. The reconstruction of the γ cluster position in the calorimeter is illustrated in Fig. 3. The logarithmic method of coordinate reconstruction with fitted parameters was chosen. The final fine-tuning of the modules' gains was made using photons from decays of neutral pions observed in the experiment.

In between the beam calibrations the gain stability of each channel was monitored by a specially designed gain light monitoring system (LMS) [9]. The LMS consists of

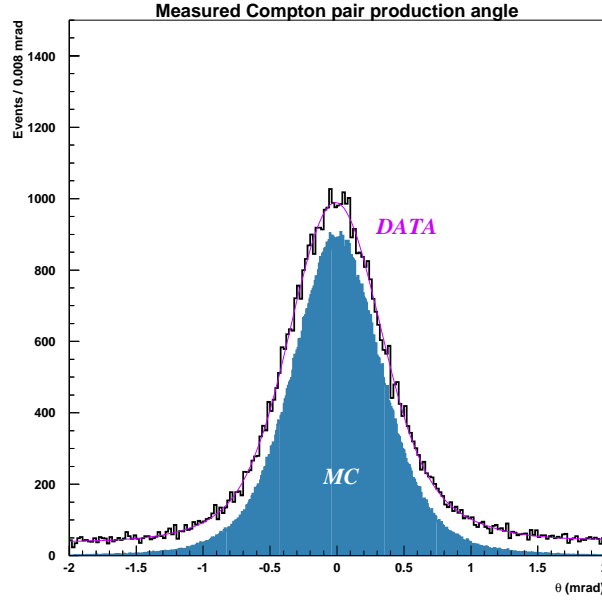


FIGURE 4. Measured angular distribution of Compton-pair clusters compared with the Monte Carlo simulations: $\sigma_{\theta} = 0.34 \text{ mrad}$.

the following main parts: a light source, a light mixing box, a light distribution system, and reference detectors with a DAQ system. The light source comprises an assembly of NICHIA super bright blue LEDs (peak wavelength 470 nm). Light mixing is done using a six inch diameter integrating sphere (ORIEL) that provided 2000 distribution channels. The pulsed light was distributed to individual calorimeter modules via a bundle of plastic optical fibers. Each fiber is attached to the front face of a detector module. As a reference detector, a Hamamatsu PIN photodiode (S3399, 3mm diameter) with an AMPTEC low noise charge amplifier was used. Light from the light monitoring system was periodically injected into the detector modules between the data taking files (~ 1 hour period).

PHYSICS RUN PERFORMANCE

The experiment took physics data in the fall of 2004. Several exposures with beryllium, carbon, tin and lead targets were taken. The performance of the calorimeter was studied using several observed physics processes: quasielastic and inelastic photoproduction of neutral pions, Compton scattering and pair production.

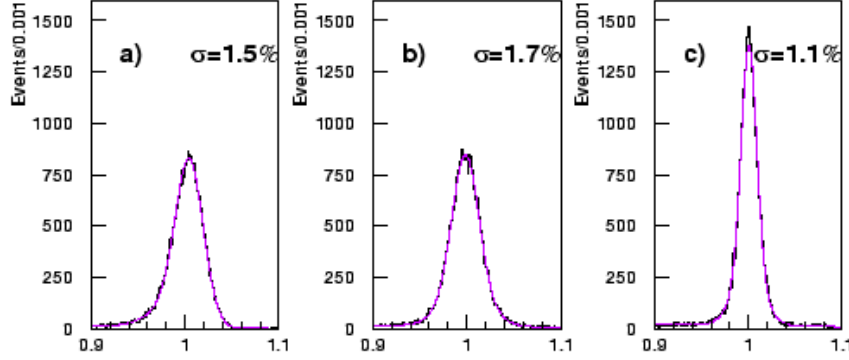


FIGURE 5. Ratio of sum of measured Compton pair energy and tagged γ energy at 5.2 ± 0.3 GeV. a - using reconstructed cluster energies; b - using cluster coordinates and Compton kinematical relations to calculate Compton pair energy; c - after applying the transverse momentum constraint.

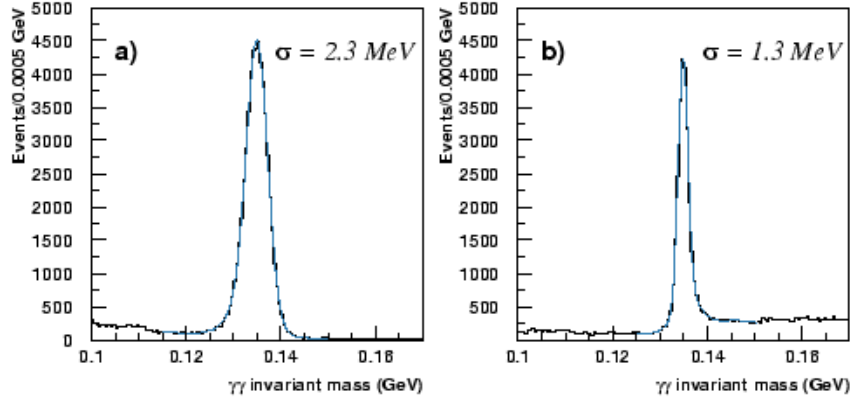


FIGURE 6. π^0 mass resolution for the $PbWO_4$ array. Left: after calibration on the nominal π^0 mass; Right: after correction on the tagged photon energy: the remaining width is mostly due to coordinate resolution.

First, we consider Compton scattering $\gamma + e \rightarrow \gamma + e$, which provides four constraints of the reaction kinematics and allows the study of energy and space resolutions of the detector, albeit in a limited range of small angles for the central $PbWO_4$ region of the calorimeter. Plotted in Fig. 5 is the ratio between the total energy as measured by the calorimeter and incident energy of the tagged photon (~ 5.2 GeV). The width of the distribution is $\simeq 1.5\%$ in (a) where complete information from the calibration is used, and $\simeq 1.7\%$ in (b) where the energy of the Compton pair is estimated only from the reconstructed shower coordinates using the kinematics of Compton scattering. The latter demonstrates the importance of good spatial resolution. As soon as total transverse momentum of the two showers is constrained to zero ($\vec{P}_T = 0$), the width of the distribution reduces to mere 1.1%, see Fig. 5c. As the Compton pairs are emitted at zero angle to the incident beam, the width of the distribution of the observed angle

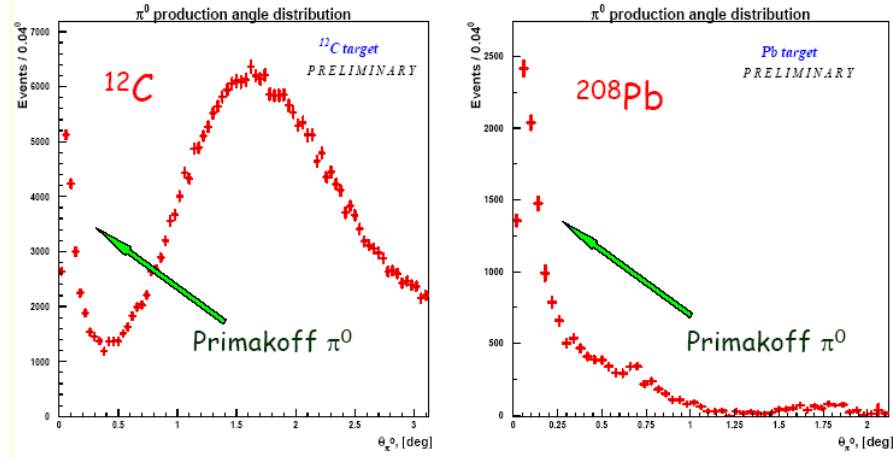


FIGURE 7. π^0 angular distribution for production on Carbon and Lead. The Primakoff production peak is clearly visible at small angles.

θ is a direct measure of the angular resolution of the detector. From the data of Fig. 4 we estimate the experimental resolution on θ as $\sigma_\theta = 0.34$ mrad, which agrees with the simulated value and is sufficient for measuring the Primakoff reaction.

Next, we estimate the detector resolution on the π^0 mass. Fig. 6 shows the $\gamma - \gamma$ invariant mass distribution for the central ($PbWO_4$) region of the calorimeter. The left-hand panel shows the distribution upon calibration on the nominal mass of the neutral pion (observed width of $2.3 \text{ MeV}/c^2$). In the right-hand panel, correction of the primary tagged photon energy has been applied. The observed width of $1.3 \text{ MeV}/c^2$ in the latter case reflects the coordinate resolution of the calorimeter. The constraint on the primary energy significantly improves the mass resolution. In addition, we see a high mass tail of the peak that is due to inelastic π^0 production. These pions have lower energy, and the beam-energy constraint shifts their corrected masses towards higher values.

The gaussian width of the π^0 peak increases from $1.3 \text{ MeV}/c^2$ for the $PbWO_4$ area of the calorimeter to $2.6 \text{ MeV}/c^2$ for the border area (on the $PbWO_4$ side of it), and to $4.5 \text{ MeV}/c^2$ for the middle of the lead-glass area.

The success of the experiment largely depends on accurate reconstruction of π^0 mesons emitted at small angles. Shown in Fig. 7 are the preliminary data on π^0 angular distributions for quasielastic production on carbon and lead nuclei. The Primakoff production peak is clearly seen for both data sets. The latter demonstrates good performance of the calorimeter, which should be adequate for a precision measurement of the π^0 lifetime.

CONCLUSION

The high precision hybrid electromagnetic calorimeter (HYCAL) has been designed, constructed, and run in the experiment aimed at measuring the lifetime of the neutral pion via the Primakoff effect. Measured characteristics of the detector have been shown

to match the design parameters. The energy resolution of the calorimeter is about 1.5% for a photon energy of 5 GeV . Angular resolution of 0.34 mrad for Compton production is achieved. The π^0 mass resolution (upon constraining the beam energy) is $\sigma = 1.3 MeV/c^2$ for the central PWO part of the calorimeter. High-quality data sets for extracting the π^0 lifetime have been collected. The first results are expected by the end of this summer. The authors thank all PrimEx collaborators for excellent design, construction, running, and data analysis of the experiment. Stable operation of the CEBAF accelerator is gratefully acknowledged. The work was supported by the US NSF grant (PHY-0079840) and the RFBR grant (04-02-17466).

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